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Feedbacks of windthrow for Norway spruce and Scots pine stands under changing climate

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Abstract

Wind damage is one of the major natural disturbances that can occur worldwide in most types of forests. Enhanced management using adequate decision support systems (DSS) can considerably reduce the risk of windthrow. The decision support system 'Forest and Climate Change' (DSS-WuK) which is currently being developed at Göttingen University aims at providing a tool for the quantitative assessment of biotic and abiotic risks for forest ecosystems under the conditions of changing climate. In order to assess the future risks of wind damage the system employs a coupled modelling approach combining the turbulence model SCALAR DISTRIBUTION (SCADIS) with the soil-vegetation-atmosphere-transfer (SVAT) model BROOK 90. The present study investigates projections of wind damage in Solling, Germany under climate scenarios A1B and B1, taking into account the windthrow feedbacks—changes of microclimate as a result of tree fall and consequent stabilization or destabilization of a forest stand. The results of the study indicate that in Solling the risk of windthrow for spruce and pine forest stands is likely to increase considerably during the 21st century. The general tendencies indicate that under A1B the probability of damage would be higher than under B1 and that under the same climate and soil conditions the risk for spruce stands would be higher than for pine stands of equal age. The degree of damage and feedback contribution as well as a sign of feedback in each particular case will strongly depend on the particular local or regional combination of climatic and soil factors with tree species, age and structure. For Solling the positive feedback to local climatic forcing is found. The feedback contributes considerably (up to 6% under given conditions) to the projected forest damage and cannot be neglected. Therefore, the adequate projection of future damage probabilities can be performed only with a process-based coupled soil-atmosphere model with corresponding high spatial and temporal resolution.

Keywords: windthrow, climate change, feedback, boreal forest

1. Introduction

Wind damage is one of the major natural disturbances that can occur in most types of forests worldwide. Following Gardiner

et al (2008) we will call henceforth any wind-induced damage leading to tree mortality—uprooting or stem breakage—a 'windthrow'. Several studies pointed out that enhanced management using adequate decision support systems (DSS)

Table 1. Structural characteristics and model parameters for age classes of two chosen tree species: Norway spruce and Scots pine.

Parameter	Unit	Norway spruce			Scots pine			Source
Age	years	45	65	85	45	65	85	a
Stand density	Trees ha ⁻¹	1913	1128	706	1608	857	561	a
Tree height	m	14.9	22.0	26.6	14.5	19.1	22.3	a
DBH	m	15.1	21.3	27.9	15.3	21.7	27.2	a
Max. leaf conductance	cm s ⁻¹	0.53	0.53	0.53	0.53	0.53	0.53	b
Max. leaf area index	m ² m ⁻²	4.55	4.67	4.20	3.09	2.74	2.50	c
Relative winter LAI	(—)	0.8	0.8	0.8	0.6	0.6	0.6	d
Fine root length	m m ⁻²	3100	3100	3100	3100	3100	3100	b
Critical leaf water pot	MPa	−4.5	−4.5	−4.5	−5.3	−5.3	−5.3	e
Albedo	(—)	0.14	0.14	0.14	0.14	0.14	0.14	b
Albedo with snow	(—)	0.14	0.14	0.14	0.14	0.14	0.14	b

^a Schober (1995). ^b Federer *et al* (2003).

^c Ahrends *et al* (2009). ^d Hammel and Kennel (2001).

^e Czajkowski *et al* (2009).

can considerably reduce the risk of windthrow (Gardiner *et al* 2000). Such DSS, however, are few (Peltola *et al* 2000, Schelhaas *et al* 2007). The decision support system ‘Forest and Climate Change’ which is currently being developed at Göttingen University will provide a tool for the quantitative assessment of biotic and abiotic risks for forest ecosystems under the conditions of changing climate (Jansen *et al* 2008).

According to Leckebusch *et al* (2007) ongoing climate change may result in the increased frequency of severe storms which in turn will produce wide-area damage events within forest ecosystems. The review of scientific literature by Albrecht *et al* (2008) demonstrated, however, that the uncertainties of the projections for future storm strengths and frequencies are too large to develop a reliable adaptation strategy. On the other hand, Peltola *et al* (1999) indicated that the projected warmer weather is expected to increase the windthrow risk as the tree anchorage in winter will be reduced due to a decrease in soil freezing. The increase of projected temperature is well supported by the results of climate modelling (IPCC 2007). Therefore, we can assume that, even if the strength and frequency of storms will remain at the same level as at present, the risk of wind damage can still increase due to the higher soil temperature and consequent reduction of tree anchorage. Thus, the risk of windthrow should be estimated as a result of the combined effect of biotic and abiotic factors (Gardiner *et al* 2000, 2008). It is also very important to take feedback of each damage event on climatic forcing into account as demonstrated by Vygodskaya *et al* (2007). The positive feedback of windthrow events on wind forcing in a forest gap was demonstrated by Panferov and Sogachev (2008) with the modified 3D atmospheric boundary layer (ABL) model SCADIS (Sogachev *et al* 2002). Schelhaas *et al* (2007) showed that the wind damage occurred not only on forest edges but also in the middle of stands. The feedback of windthrow is not limited to the increase of windload on the remaining trees around the gap (Panferov and Sogachev 2008). The feedback can be related to many other processes and can have both positive and negative effects—the changes of precipitation interception, water regime, radiation—to name a few. The present study focuses on investigation of such effects for two typical boreal tree species: Norway spruce and

Scots pine and for six soil types under the projected climatic conditions of SRES A1B and B1.

2. Methods

2.1. Site description, tree species, soil conditions

The Solling highlands within the limits of 51.6°N to 52°N and 9.4°E to 9.8°E, i.e. about 1600 km², are chosen for the investigation. Two tree species: Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus Sylvestris*, L.) with three age classes each are studied. The corresponding characteristics of all species’ classes are given in table 1.

In order to consider the effects of different soil types and soil textures on root–soil resistance, rooting depth and soil moisture, we have selected six different soils from the digital soil map of Germany (Richter *et al* 2007), which are typical for the investigation area. All six soils are free draining soils, but with strongly contrasting physical characteristics, e.g. texture, stone content and thickness (table 2).

2.2. Climate projections

To represent possible future climatic conditions the calculations of two SRES climate scenarios A1B and B1 for the period of 2001–2100 as well as the 20th century scenario C20 for the period of 1960–2000 done by the coupled general circulation model—Max-Planck-Institute ocean model, ECHAM5-MPIOM, were used as defined in the German framework programme ‘klimazwei’. The modelled data were downscaled using the Climate Local Model, CLM (Rockel *et al* 2008) to a spatial resolution of 0.2° × 0.2°. The daily mean values of climate variables for A1B, B1 and C20 with two runs per scenario were obtained from the CERA database (Lautenschlager *et al* 2009). For all meteorological variables the time series of all available runs of A1B and B1 (1 and 2) were merged with corresponding runs of C20 so that continuous time series from 1960 to 2100 were built for both runs of A1B and B1. The following notation is assumed in further analysis: A1B_1, A1B_2 and B1_1 and B1_2 which are correspondingly the merged runs 1 and 2 of C20–A1B and C20–B1. The simple A1B and B1 denote respective merged scenarios averaged over the two runs.

Table 2. Soil hydraulic parameters by texture class from Clapp and Hornberger (1978) at saturation (subscript ‘s’) and at the upper limit of available water (subscript ‘u’). (Note that where BD is bulk density, ψ is matrix potential, K is hydraulic conductivity and θ is volumetric water fraction. Soil types and horizon symbols are given according to FAO (1990).)

Soil type	Depth (cm)	Horizon	Texture	Stone (%)	BD (g cm ⁻³)	Ψ_u (kPa)	θ_u	θ_s	K_u (mm day ⁻¹)
Vertic cambisol	2–0	L/F	—	0	0.2	–34.4	0.650	0.863	3.70
	0–5	Ah	Clay loam	1.5	1.35	–14.8	0.402	0.476	7.31
	5–15	Ah/Bw	Silty clay loam	1.5	1.35	–6.0	0.397	0.477	4.87
	15–40	Bw	Silty clay loam	9	1.35	–6.0	0.397	0.488	4.87
	40–60	2Bv	Clay	50	1.75	–7.7	0.425	0.482	4.31
	60–200	2R	Clay	92.5	1.65	–7.7	0.425	0.482	4.31
Cambisol (depth)	4–0	L/F	—	0	0.2	–34.4	0.650	0.863	3.70
	0–5	Ah	Silt loam	9	1.15	–25.0	0.365	0.509	13.13
	5–90	Bw	loam	9	1.35	–8.5	0.324	0.472	6.27
	90–200	2C	Loamy sand	72.5	1.75	–3.8	0.203	0.410	3.51
Cambisol (shallow)	4–0	L/F/H	—	0	0.2	–34.4	0.650	0.863	3.70
	0–10	Ah	Silt loam	27.5	1.15	–25.0	0.365	0.550	13.13
	10–25	Bw	Silty clay loam	50	1.35	–6.0	0.397	0.488	4.87
	25–35	Bw/C	Silty clay loam	50	1.75	–6.0	0.397	0.477	4.87
	35–50	C	Clay	72.5	1.95	–7.7	0.425	0.482	4.31
	50–200	R	Clay	92.5	1.65	–7.7	0.425	0.482	4.31
Stagnic luvisol	7–0	L/F/H	—	0	0.2	–34.4	0.650	0.863	3.7
	0–30	Ah	Silt	1.5	1.55	–25.0	0.365	0.485	13.13
	30–50	Bw/Bg	Silt loam	1.5	1.75	–25.0	0.365	0.485	13.13
	50–100	Bg/Bt	Silt loam	9	1.75	–25.0	0.365	0.485	13.13
	100–130	Bt/Bg	Silt loam	9	1.75	–25.0	0.365	0.485	13.13
	130–200	Bw	Silt loam	27.5	1.75	–25.0	0.365	0.485	13.13
Cambic podzol	8–0	L/F/H	—	0	0.2	–34.4	0.650	0.863	3.7
	0–5	A Eh	Silt loam	50	1.35	–25.0	0.365	0.485	13.13
	5–10	Bw(A Eh)	Silt loam	50	1.35	–25.0	0.365	0.485	13.13
	10–30	Bw	Silt loam	50	1.55	–25.0	0.365	0.485	13.13
	30–60	Bw2	Silt loam	72.5	1.55	–25.0	0.365	0.485	13.13
	60–200	R	Silt loam	92.5	1.98	–25.0	0.365	0.485	13.13
Podzol	9–0	L/F/H	—	0	0.2	–34.4	0.650	0.863	3.70
	0–10	AhE	Sand	1.5	1.15	–7.0	0.188	0.509	3.96
	10–25	AE	Sand	1.5	1.35	–7.0	0.188	0.450	3.96
	25–30	Bh	Sand	1.5	1.55	–7.0	0.188	0.395	3.96
	30–40	B	Sand	1.5	1.55	–7.0	0.188	0.395	3.96
	40–80	C	Sand	1.5	1.55	–7.0	0.188	0.412	3.96
	80–200	C	Sand	1.5	1.55	–7.0	0.188	0.412	3.96

2.3. Critical wind speed

The critical wind speed (CWS) for windbreak, CWS_{break} , and for overturning, CWS_{ot} , defined as the speed at the tree tops are calculated as in ForestGALES. The detailed description and discussions of the approach are given in Gardiner *et al* (2000, 2008), Achim *et al* (2005), Quine and Gardiner (2007). Here the main equations are shown:

$$CWS_{\text{break}} = \frac{1}{\kappa D} \left[\frac{\pi \text{MOR} * \text{DBH}^3}{32 \rho G (d - 1.3)} \frac{f_{\text{knot}}}{f_{\text{CW}}} \right]^{\frac{1}{2}} \ln \left(\frac{h - d}{z_0} \right) \quad (1)$$

$$CWS_{\text{ot}} = \frac{1}{\kappa D} \left[\frac{C_{\text{reg}} * \text{SW}}{32 \rho G d} \frac{f_{\text{knot}}}{f_{\text{CW}}} \right]^{\frac{1}{2}} \ln \left(\frac{h - d}{z_0} \right) \quad (2)$$

where $\kappa = 0.41$ is von Karman’s constant, d (m) is the zero-plane displacement, z_0 (m) is the aerodynamic roughness, D (m) is the average spacing between trees (table 1), DBH (m) is diameter at breast height (1.3 m above ground), h (m) is mean tree height (table 1) and ρ (1.226 kg m⁻³) is the dry air density. C_{reg} (N m kg⁻¹) is a regression constant that is dependent on soil and rooting depth and SW (kg) is the stem

weight of the tree. The factors f_{knot} ($=0.85$) and f_{CW} ($=1.17$) account for the reduction in wood strength due to knots and the additional load due to the overhanging weight of the tree displaced from the vertical position by the wind stress. f_{edge} , taking into account the position of the tree relative to the forest edge, is ignored because of the assumption of horizontal homogeneity. G is a dimensionless gust factor (Gardiner *et al* 1997, Achim *et al* 2005):

$$G = 18.585 - 28.35 \frac{D}{h} + 1.59165 \ln \left(\frac{D}{h} \right). \quad (3)$$

The influence of rooting depth was taken into account. We assume that the tree anchorage and consequently the CWS estimated by means of functions based on tree pulling experiments are valid for ‘average’ species-specific rooting depths: 1.04 m for spruce and 1.3 m for pine. Then the deviations of rooting depths from these mean values caused by a combination of tree species and soil type (Lehnardt and Brechtel 1980, Raissi *et al* 2009) produce a corresponding linear positive or negative deviation from mean tree anchorage (Blackwell *et al* 1990, Peltola *et al* 1999, Nicoll *et al* 2006) and, thus, deviations of CWS from the initial ‘average’ value.

In general, the risk of windthrow increases with increasing soil moisture content because of the weakening of tree anchorage and consequent reduction of CWS (Stathers *et al* 1994). As a dynamic indicator of the soil moisture status, we use the time-dependent relative extractable soil water, REW(*t*), which is calculated with the daily timestep as the ratio of actual to maximum extractable water according to García-Santos *et al* (2009)

$$\text{REW}(t) = \frac{\theta_v(t) - \theta_R}{\theta_{fc} - \theta_R} \quad (4)$$

where θ_v ($\text{m}^3 \text{m}^{-3}$) is the actual (correspondingly—daily) volumetric (subscript ‘v’) soil water fraction; θ_{fc} ($\text{m}^3 \text{m}^{-3}$) is the maximum soil water content extractable by plants (subscript ‘fc’ means field capacity) and θ_R ($\text{m}^3 \text{m}^{-3}$) is the residual soil water content. We distinguish between dry and wet soil conditions where the wet conditions mean that the soil moisture has exceeded a certain threshold and the tree anchorage starts to decrease. As there are no published data on the critical level of soil moisture, the threshold of $\text{REW}(t) \geq 0.6$ is chosen in this study because at this level the optimum water content has been exceeded (Howard and Howard 1993, Walse *et al* 1998, Wildung *et al* 1975). The rate of mineralization, used as a proxy, slows down which indicates the prevailing anaerobic conditions and consequently filling most soil pores with water. The moistening of the soil beneath a soil–root plate reduces the tree’s resistance to wind (Kamimura *et al* 2009). Therefore, we assumed for free draining soils that when a REW(*t*) exceeds 0.6 the CWS decreases linearly:

$$\text{CWS}(t) = \begin{cases} \frac{\text{CWS}_{\text{ot}} * 0.6}{\text{REW}(t)}; & \text{REW}(t) \geq 0.6 \\ \text{CWS}_{\text{break}}; & \text{REW}(t) < 0.6. \end{cases} \quad (5)$$

2.4. Soil water

To simulate the water balance of a given combination of tree species and ages with certain soil types the 1D-SVAT model BROOK90 (version 4.4e) is used (Federer 1995, Federer *et al* 2003). It is a detailed, process-oriented model that can be used as a reliable tool to investigate the potential effects of changes in tree species, soil types and climate scenarios. For all tree species—soil type combinations—free drainage is accepted as the lower boundary condition at 2 m depth. For each soil horizon the parameters of the water retention curve and the hydraulic conductivity function are deduced from soil texture with the pedotransfer function of Clapp and Hornberger (1978). The porosity values are corrected according to Federer *et al* (1992). For the soil textural classification the program TRIANGLE of Gerakis and Bear (1999) is implemented.

The architecture of root systems is mainly influenced by the parent material, soil type, bulk density, chemical soil conditions, depth of ground water, tree species and age. However, in each particular situation the information on rooting depth and the root distribution within the soil profile is a main source of uncertainty. For estimation of the effective rooting depth the rules from Raissi *et al* (2009) are applied. The relative root density is modelled as a function of soil depth (Jackson *et al* 1996).

The BROOK90 calculations for all climate scenarios and runs were started at the timepoint 01.01.1960 and carried out with daily timesteps continuously for 140 yr up to 2100. The evaluations of results were accomplished for the following four periods: P0: 1981–2010—assumed as the ‘present conditions’ or reference period, P1: 2011–2040, P2: 2041–2070 and P3: 2071–2100.

2.5. Risk assessment and feedbacks

In the numerical experiments the following assumptions are made: (1) all forest stands are unmanaged; (2) no large gaps result from windthrow events—the windthrow damage is distributed evenly within the forest stand and (3) the surviving trees are quantified as a share of total stand ($0 \leq \text{ST} < 1$) which is a function of windload. The minimal wind speed causing a windthrow is $V_{\min} = 8 \text{ m s}^{-1}$ (the corresponding load is denoted as $F_{V \min}$) and the wind speed of $V_{\text{abs.max}} = 40 \text{ m s}^{-1}$ is set as the load of full damage (Schelhaas *et al* 2007) (the corresponding load is denoted as $F_{V \text{ abs,max}}$). The relative load provided by the actual wind is then

$$F_{\text{act}} = 1 - \frac{F_{V \text{ abs,max}} - F_{V \text{ act}}}{F_{V \text{ abs,max}} - F_{V \min}} \quad (6)$$

and

$$\text{ST} = 1 - F_{\text{act}}^b,$$

where $b = 3.73$ is the best approximation of damage curves for unmanaged stands presented by Schelhaas *et al* (2007).

To assess the effects of forest structure changes resulting from windthrow events on the probability of the next damage event the calculations are carried out in two ways. First, the damage is summed up during the 30 yr period, but the forest structure is not changed. Second, the damage is summed up and the damaged trees are ‘removed’ from the stand; accordingly the stand density and leaf area index, LAI, decrease. The calculations with BROOK90 continued from the timepoint of damage with the new values of structural characteristics. The changes in structure result in a stand’s microclimate changes, which might enhance or inhibit the next windthrow event, thus creating positive or negative feedback.

3. Results and discussion

To characterize the projected climate conditions in the 21st century in the Solling area the CLM data were post-processed according to the recommendations of Keuler *et al* (2007). The data of A1B_1, A1B_2, B1_1 and B1_2 are aggregated to annual means (sums in the case of precipitation). Spatial averaging over the 9 CLM grid points representing the study area is carried out for all mentioned climate characteristics. The spatial variations within the chosen area are very low (coefficient of variation $< 10^{-2}$) so that the spatial means are assumed to be representative. To describe the tendencies of climate development the spatial mean values are averaged over the 30 yr periods: P0–P3 and relative differences are calculated: $\Delta\varphi_i = (\varphi_i - \varphi_0)/\varphi_0 * 100\%$, where φ_i is the 30 yr mean value of the spatially averaged climate variable listed above for the climatic period $i = 1, 2$ and 3 and φ_0 is the mean value of the same variable for P0: 1981–2010.

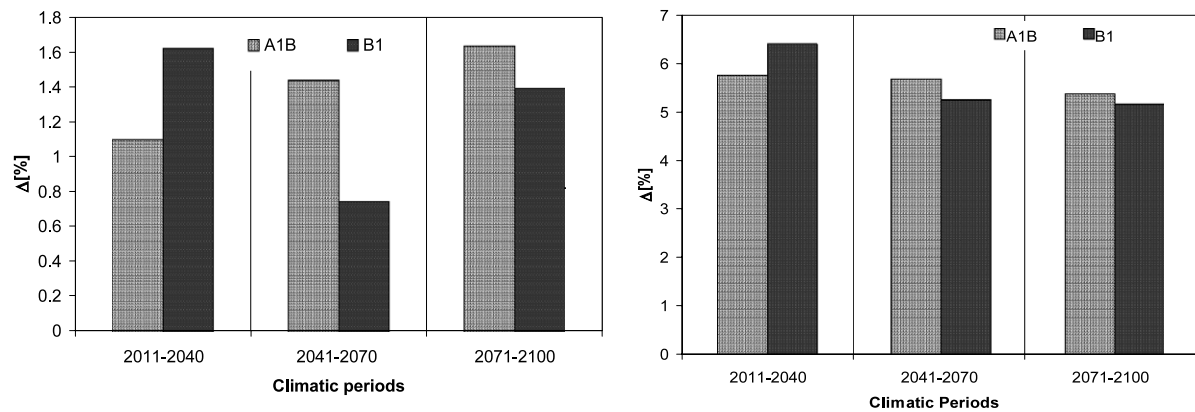


Figure 1. The changes of annual mean values of V_{max} (left panel) and precipitation sum (right panel) averaged over 30 yr climatic periods relative to the reference period P0 (1981–2011) for two SRES scenarios, A1B and B1.

The analysis of climate scenarios' data shows that in both A1B and B1 the daily averaged maximal wind velocity (V_{max}) does not change strongly during the 21st century (figure 1). In A1B V_{max} increases continuously towards P3 with increasing $\Delta V_{max,3}$ going up to 1.6%. In B1 the strongest increase of 1.6% for ΔV_{max} occurs from P0 to P1, exceeding the corresponding $\Delta V_{max,1}$ value for A1B. The precipitation sums vary slightly stronger. Both scenarios project a weak increase of precipitation to $\Delta P_1 \approx 6\%$ and then monotonically decrease weakly towards 2100 to $\Delta P_3 \approx 5\%$. However, the air and soil temperatures increase monotonically and rather strongly towards P3 with $\Delta T_3 > 37\%$ in A1B and $\Delta T_3 > 24\%$ in B1 (not shown here).

To characterize the differences in risk probabilities between tree species and soil types and to show the future projected development of risks relative to the present conditions the risks are presented at first as the absolute values (figure 2) and then as relative increments normalized by the damage values of the 'present conditions' period P0 (figure 3). Figure 2 clearly demonstrates the strong variations of risk probability depending on the particular combination of influencing factors. The magnitudes of risks generally remain below 20% (>80% of stands survive during the 30 yr period) except for the spruce growing on shallow cambisol under the conditions of A1B. Figure 2 shows that, under the same conditions (climate scenarios, soil types and stand age), spruce stands have higher wind damage risk than pine stands, except for 45 yr old trees on shallow cambisol where the risks are almost equal (up to 18%). However, for each particular case this general rule cannot be applied and all factors should be taken into consideration. For instance, one can see that pines on shallow cambisols have higher risk probabilities than spruces of the same age on stagnic luvisol under both scenarios, and even that young pines on shallow cambisols have higher risks than spruces of all ages on almost any other investigated soil type. The 85 yr old pine on deep cambisol has higher risks (up to 8%) than 65 yr old spruce on stagnic luvisol (up to 6%) for both A1B and B1. Considering the influence of soil conditions another general dependence could be found: for all scenarios, tree species and ages the highest risk probability is shown by the shallow cambisols and the lowest by stagnic

luvisols and podzols (slightly higher than stagnic luvisols). The moderate values for deeper cambisol, vertic cambisol and cambic podzol lie between these extremes and are very close to each other. Interestingly, for the youngest (45 yr old) trees the influence of soil type is higher for pine, where the difference in damage between lowest and highest risks reaches 8%, than for spruce (difference within 1%). For the 65 and 85 yr old trees the tendency is opposite—the soil-dependent variability of windthrow risks is generally higher for spruce than for pine. Studying the effect of stand age one can see that the highest risks are in youngest spruce and pine stands on all soils with the exception of middle and older spruces on shallow cambisol. Those mostly stable for spruce and pine stands are the 65 yr old ones which show H/BHD ratio and stand density providing the highest resistance and thus the highest CWS.

The right panels for both species in figure 2 show the contributions of feedbacks to the wind damage. When stand structure is adjusted according to the damage the projected risks generally increase, performing a positive feedback. The feedbacks contribute up to 5% in B1 and up to 6% in A1B to the initial wind damage. This effect is caused by the joint influence of several factors: the windthrow leads to a reduction of stem density in a stand and to a reduction of LAI. The lower LAI in its turn causes the increase of radiation input and evaporation, but a decrease of transpiration and precipitation interception. The total observed effect under the particular climatic and soil conditions is the increase of the soil water content which leads to the reduction of CWS and, thus, to an increase of the probability of following windthrow.

The magnitude of the feedback contribution depends on all factors. It visibly increases with the stand age for both species, adding up to 6% to the risks of the oldest spruce stands and up to 3% to the risks of the oldest pines. The age dependence is presumably caused by the high sensitivity of CWS to the combined influence of stand density with tree height which increases exponentially with age. The observed differences between tree species are rather remarkable: the contribution of feedback is stronger for the youngest pines than for the youngest spruces, but weaker for middle and older pines compared to spruce stands of the same ages. The influence of the soil type on the feedback contribution is quite strong,

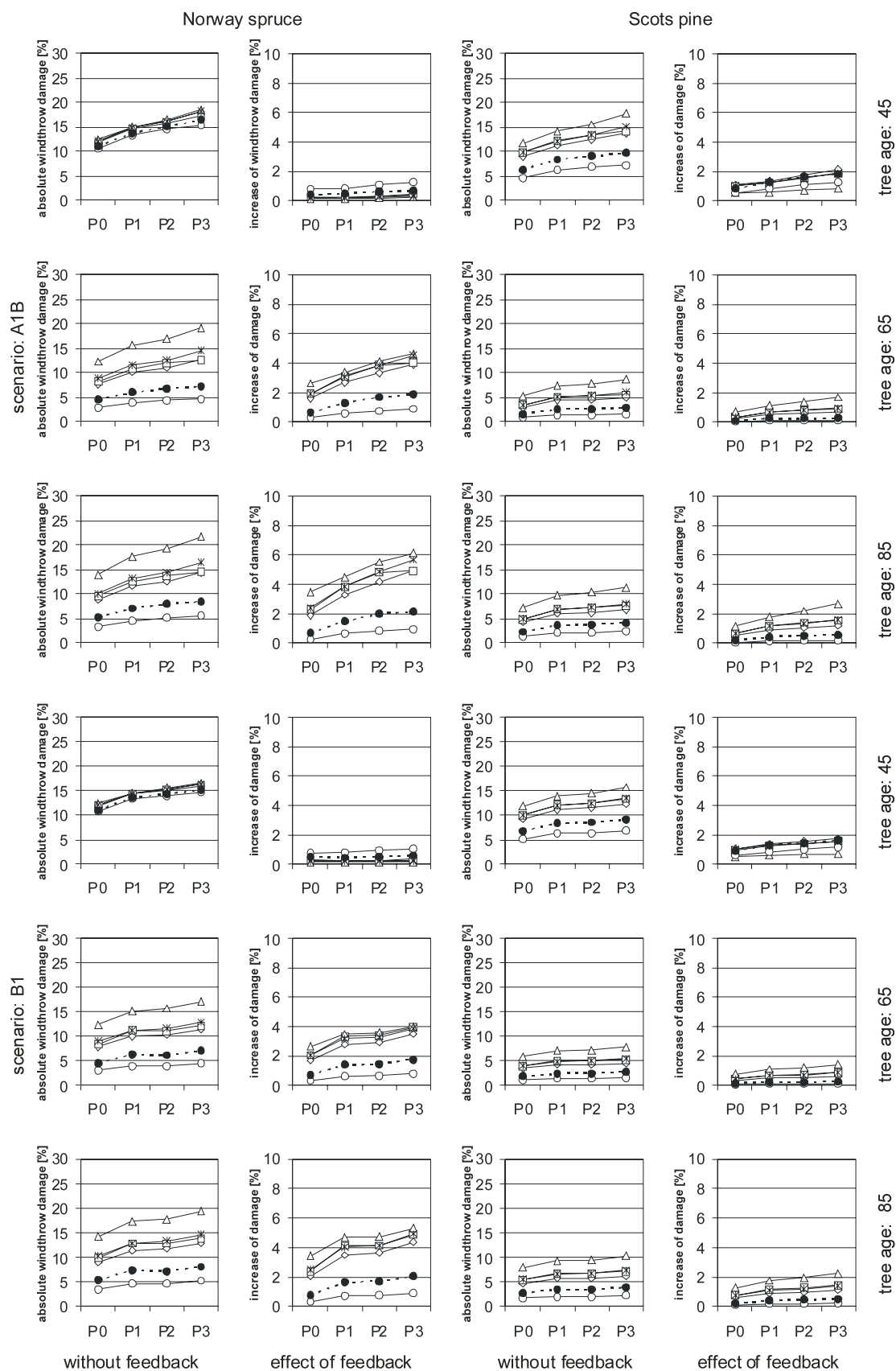


Figure 2. Scenarios of absolute windthrow damage (%) as a share of total stand for different tree species, tree ages and soil types. — △ —: cambisol (shallow), — ● —: podzol, — ○ —: stagnic luvisol, — □ —: cambisol (deep), — ◇ —: vertic cambisol, — × —: cambic podzol.

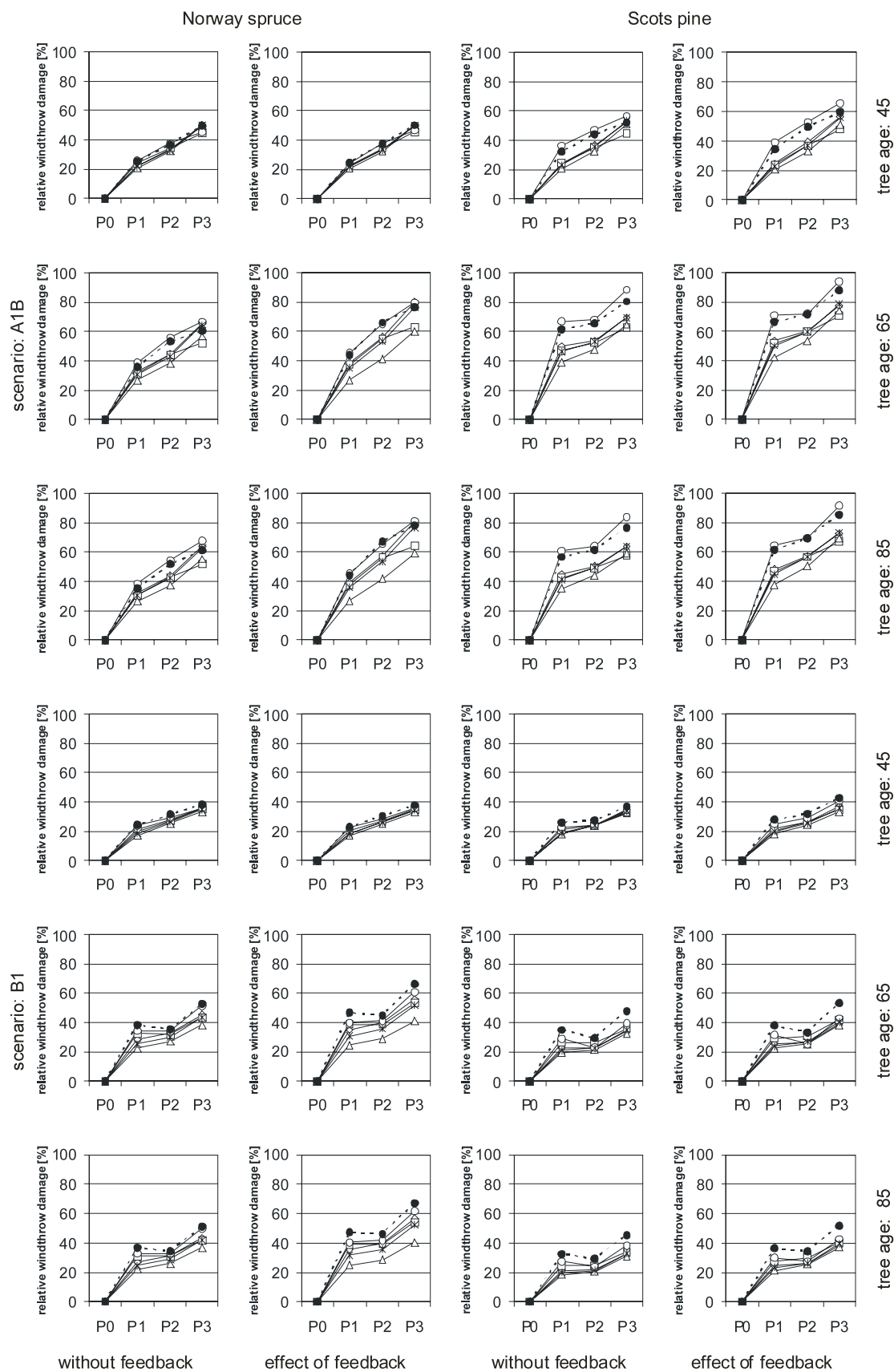


Figure 3. Scenarios of relative windthrow damage (%) as a share of total stand for different tree species, tree ages and soil types. — △ —: cambisol (shallow), — ● —: podzol, — ○ —: stagnic luvisol, — □ —: cambisol (depth), — ◇ —: vertic cambisol, — × —: cambic podzol.

but varies significantly between different combinations of tree species with stand ages. Some general rules could, however, be deduced: in 65 and 85 yr old spruce and pine stands the feedback provides the strongest contribution on the ‘highest risk’ soils like shallow cambisols, and the lowest contribution on the lowest risk soils like stagnic luvisols. The pattern for the youngest stands is somewhat more complicated: with spruces the order is reversed—lowest risk soils like podzols get the highest and stagnic luvisols the lowest contribution; with pines the stagnic luvisols also gets the smallest contribution: the highest contribution, however, is observed for vertic cambisols. In terms of climatic conditions the risks for all species, stand ages and soil types are generally lower under B1 than under A1B for which the higher wind speeds are projected.

3.1. Projected relative changes of windthrow

When estimating the trends of windthrow risks in the 21st century compared to present conditions, i.e. relating the projected damage for periods 1, 2 and 3 to the reference P0 (figure 3), it is obvious that the values generally increase towards 2100. The increment reaches values as high as 90% for 45 yr old pines under A1B. As the relative changes of V_{\max} towards P3 are rather weak—within 2%—the considerable increment of damage could be explained by the reduction of CWS caused by a combined effect of soil moisture increase due to the increase of precipitation (figure 1) with an increase of air and soil temperature. On the one hand, the increase in temperature increases the evaporation which has a drying effect leading to stabilizing of stands and increasing of CWS. However, on the other hand the rise of temperature leads to the destabilization of stands via the increasing share of liquid precipitation and the decreasing number of days with ground frost, thus decreasing the CWS. The resulting effect for the studied conditions is destabilizing, i.e. leads to the decreasing of CWS and increasing of wind damage risks. The changes, i.e. relative increases of risks, are generally stronger under A1B conditions (e.g. >50% for P3) than under B1 (<50% for P3). However, the temporal course of changes and the relative contribution of feedback are of a more complicated character depending on a combination of scenarios, tree species and soil types (figure 3). For all 65 and 85 yr old stands under B1 and for 65 and 85 yr old pine stands under A1B the curves show a period between P1 and P2 where both the increase of relative risks and feedback contributions slow down (e.g. 65 yr old pine), remain at the same level or even decrease. The effect is caused by the combined effect of precipitation and windspeed changes: an increase of the annual values of both causes the strong increase of damage risks during P1 relative to P0 under both A1B and B1. However, the weaker increment of annual precipitation during P2 slows down the relative increase of damage under A1B and the simultaneous weak reduction of precipitation with strong reduction of windspeeds (figure 1) causes with some soils (e.g. podzols) even a negative trend for P2 compared to P1. The strong increase of the windspeed during P3 combined with a stabilization of annual precipitation causes the second strong increase from P2 to P3 of projected damage relative to present conditions (P0). The pattern of

relative damage with feedback contributions (figure 3, right columns by both species) is similar to the pattern of relative damage itself, but shows higher values for all species and soils. For all the spruce stands and youngest pine stands under A1B the risks and feedback contributions increase monotonically toward P3. The youngest spruces under B1 show the same monotonic increase despite the irregular changes of wind speed described above. It is caused by the increase of air and soil temperatures and by seasonal distribution of precipitation and CWS during the 21st century. It means: the mentioned reduction of annual precipitation and wind speed increments are caused by the reductions of summer half-year values while both the winter precipitation and the number of days with CWS increase toward 2100, causing monotonic damage increase by shallow-rooted spruce and youngest pine compensating for the reduction during the summer months.

Comparing the risk increments of both species one can notice that risk increments with (up to 95%) and without feedbacks (up to 90%) are higher for pine than for spruce (up to 70% and 80%, respectively) under A1B and—for youngest pine—under B1. For older stands under B1 the risks are slightly lower than for spruce. The reason is that the shallower-rooted spruce has considerably higher probability of damage already during P0 than pine (figure 2). That results in lower than pine values of relative (relative to P0) damage under the strong increase of V_{\max} during A1B and from P0 to P1 under B1. The relative values also show the role of soils. By considering figures 2 and 3 one can see that, in general, the forests on soils with high absolute values of risk damage (e.g. shallow cambisol) experience a lower relative increment both with and without feedback than the forests on ‘low damage soils’ like stagnic luvisol. This general tendency can be explained in a similar way—shallower soils are already close to ‘risk saturation’ during P0 and the high risk values of P0 results in a lower relative increment than for low risk soils. The dependence, however, is not that straightforward: under B1 the highest risk changes, with a well-expressed difference for older trees, is observed for podzols—the second lowest damage risk.

The time course of feedback contribution also depends on the combination of climatic, soil and stand factors (figures 2 and 3). For ‘risk saturated’ shallow-rooted youngest pine and spruce stands on all soils the contribution of feedback remains below 2% during all periods. The 65 and 85 yr old stands experience an increase of feedback contribution towards 2100 for all soils except for podzol and stagnic luvisol, where the contributions stabilize around P2 and show no or very weak increase towards P3. It should be noted that the feedback contribution for spruces increases with stand age from up to 5% for 65 yr to 6% for 85 yr old stands and from up to 4% to 5% under B1. Also the feedback contribution for both older pine stands on podzol and stagnic luvisol reach maximum risks in P1 and remain at this level till P3. The feedback contribution to risks in pine stands generally remains very low, exceeding 2% for 85 yr old stands only on highest risk shallow cambisols. The higher resistance of pine could be explained by the stronger role of deep rooting which compensates for the destabilizing effect of feedback, namely the increase of REW caused by LAI reduction through the windthrow.

4. Conclusions

The results of the study indicate that in Solling, Germany the risk of windthrow for spruce and pine forest stands is likely to increase considerably during the 21st century, although the projected increases of windspeed and annual precipitation sums are rather weak (up to 1.6% and 6.5%, respectively). The general tendencies indicate that under A1B the probability of damage would be higher than under B1 and that under the same climate and soil conditions the risk for the spruce would be higher than for the pine stands of equal age. However, it is shown that the degree of damage in each particular case will strongly depend on the particular local or regional combinations of tree species, age and structure with climatic and soil factors. It is also demonstrated that windthrow-caused changes of forest structure produce a positive feedback to local climatic forcing in Solling. The feedback contributes considerably (up to 6% under given conditions) to the projected forest damage and should not be neglected. However, the resulting sign of the feedback in other landscapes will depend on the interaction of separately mentioned climatic, soil and vegetation factors. Therefore, the adequate projection of future damage probabilities could be performed with a process-based coupled soil–atmosphere model with corresponding high spatial and temporal resolution, although the more accurate estimation of the REW contribution to stabilization/destabilization of trees on different soils still remains a great challenge and requires more experimental studies.

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